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The broad objectives of this grant were to enhance knowledge of underwater sound propagation in geospatially and temporally varying shallow water waveguides. More specifically, the work was focused on experimental techniques for measuring the sound field emitted by a point source or sources at ranges and depth in a shallow water waveguide. Information extracted from these measurements, in the form of normal mode characteristics, would be used as the basis for inferring geoacoustic parameters of the waveguide. During the course of this work, novel signal processing approaches and new inversion methodologies were developed and reported in the scientific literature and at international conferences. The primary data set considered was collected as part of the ONR Shallow Water 2006 experiment.

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Accounting for ocean and seabed variability in oceanic waveguide parameter estimation

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ABSTRACT

This document represents the final technical report for ONR grant number N00014-08-1-0327. The broad objectives of this grant were to enhance knowledge of underwater sound propagation in geospatially and temporally varying shallow water waveguides. More specifically, the work was focused on experimental techniques for measuring the sound field emitted by a point source or sources at ranges and depth in a shallow water waveguide. Information extracted from these measurements, in the form of normal mode characteristics, would be used as the basis for inferring geoacoustic parameters of the waveguide. During the course of this work, novel signal processing approaches and new inversion methodologies were developed and reported in the scientific literature and at international conferences. The primary data set considered was collected as part of the ONR Shallow Water 2006 experiment.

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LONG-TERM GOALS

The long-term objective of this work was to develop methods for rapid assessment of seabed variability combined with detailed localized geoacoustic inversions to characterize the bottom for shallow-water environments. Consideration was given to spatial and temporal variability of water column properties common to shallow-water environments and their impact on inversion results. Advances made in the work will contribute to development of unified ocean/ seabed/ acoustic models and improved prediction capabilities for USW tactical decision aids.

OBJECTIVES

The objective of this research was to expand our understanding of propagation in shallow waters by incorporating high-resolution measurements of both the acoustic field and the ocean environment. The scientific goals of the proposed work were to address research issues relating to parameter estimation derived from acoustic field measurements in shallow water. Parameters of interest include seabed properties (sound speed, density, attenuation) and morphology along with source location. Issues that were addressed include: parameter estimation for geospatially varying bathymetry and sediments; the impact of water column variability on geoacoustic inversion; and the effects of Doppler shift in a waveguide on acoustic measurements and inversion. Further objectives of this work were to transition the inversion approach for use with operational assets.

APPROACH

The approach focused on the continued analysis of both low-frequency acoustic and high-resolution oceanographic data collected during the Modal Inversion Methods Experiments (MIME) conducted August 2006 [A]. MIME was a component of the ONR Shallow Water 06 (SW06) experiment. Acoustic data were collected along synthetic apertures created by a towed source emitting low-frequency, continuous wave (cw) tones (50,75,125, and 175 Hz) and for a stationary source transmitting a broadband signal with 250 Hz bandwidth. Using techniques based on the short time Fourier transform, these complex pressure field data are transformed to the horizontal wave number domain. Individual values of horizontal wave numbers associated with peaks in the horizontal wave number spectrum correspond to propagating normal modes and are used as input data for geoacoustic inversion.

Analysis of the SW06 data seeks solutions to the geoacoustic inversion problem which are optimized for both efficiency and accuracy. During FY11, these same approaches were applied to data collected on operational sonobuoys. A sea trial was organized using a combination of assets previously used in the SW06 experiment. These included a J-15-3 low-frequency acoustic transmitter along with research sonobuoys developed for the ONR OA sponsored Modal Mapping Experiment (MOMAX) work. These buoys were equipped with 2 hydrophones and GPS navigation with the data recorded internally. In addition to the MOMAX buoys, AN/SSQ 53F sonobuoys equipped with GPS were procured and deployed. To obtain data at frequencies near 1 kHz, a US Navy standard G34 acoustic source was employed. These data were analyzed in FY12 and results obtained from MOMAX and operational systems compared.

In this work, emphasis was placed on developing methods capable of accounting for range-dependence in the seabed that is both directly measurable, such as bathymetry, and unknown, such as that due to intrusions or layer pinching. Alternative *regularlization methods* [2] were adapted and exploited to better constrain inverse solutions and account for layering in the seabed. The perturbative method was also expanded for use with broadband data. The work was pursued in collaboration with Megan S Ballard (Applied Research Laboratories/University of Texas at Austin, Austin, TX), George V Frisk (Florida Atlantic University, FL) and Subramaniam D Rajan (Scientific Solutions, Inc. NH).

Additional areas of research based on analysis of the collected data sets addressed the impact of watercolumn variability on wave number estimation [B][4], development of an exact inversion algorithm based on discrete reflection coefficient data obtained from wave number estimates [1], and a source depth discrimination tool based on the distribution of energy in horizontal wave number spectra. Data from SW06 was provided for testing new source localization algorithms developed by Dr. Gargeshwari Anand (Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore, India) This collaboration was started as a result of the Indo-US Workshops on Shallow-Water Acoustics, sponsored by ONR and held in India in February 2010 and again in 2011.

WORK COMPLETED

The experimental work described for SW06 was completed in August 2006. To date this work has resulted in multiple publications in refereed journals [2-6], conference proceedings, and conference presentations. In FY11, experimental work with operational assets was carried out in March 2011 on the R.V. Hugh H. Sharp, also in New Jersey shelf waters. During this trial, this project specifically supported the acquisition and processing of data received on the AN/SSQ 53F sonobuoys. Chris Miller (US Naval Post Graduate School, CA) provided the use of radio receivers capable of receiving the large bandwidth VHF signal from the sonobuoys containing the GPS and acoustics data. Chad Smith from Penn State put together the acquisition system to demodulate the VHF data and extract the acoustic and navigation data from the buoys. Acoustic data was collected on these buoys while deployed concurrently with MOMAX buoys to allow for inter-system comparison of results.

Specifically, under this grant, the following work was completed.

(1) Novel approaches to constraining the linearized inverse problem were introduced to the community for inferring waveguide geoacoustic properties. These approaches were applied to infer the properties of layered sediment models with spatial variability. They were also applied to estimate range-dependent water column sound speed. [2-5]
(2) The application of high-resolution wave number estimation techniques was optimized for extracting range-dependent modal information used in the inversion algorithms. [C]
(3) Spatial maps of seabed properties were inferred from modal dispersion data measured on sources and receivers distributed arbitrarily in the waveguide. [6]
(4) The inversion approach was applied to data collected on operational sonobuoys.

RESULTS

Many of the results from this work have been documented through numerous invited conference presentations as well as in the published literature – see publications list. The interested reader is referred to the literature for details. An overview of significant results stemming from the basic research and in the literature is given here.

Data collected on a vertical array of hydrophones during SW06 for a towed continuous wave source operated at 50 Hz and at constant depth are shown in Fig. 1 along with the track geometry. Data shown in the figure at multiple depths is displayed for two different data collects along the same track separated in time by 5 hours. The observed differences were ascribed to differences in the oceanographic conditions. Over the corresponding five hours, significant cooling was observed in the water column at ranges far from the array. Optimizing the high-resolution wave number estimator, range-dependent wave number estimates were obtained indicating the wave number response to the cooling as indicted in Fig. 2. Based on range-dependent wave numbers estimated from track 8 data, collected when the cooler water was present, novel inversion algorithms were employed to estimate the range-dependent sound speed field in the water column along the track. The inferred sound speed field shown in Fig. 3 was in close agreement with measurements made during the experiment.

Inversion for geospatially varying sound speed in the sediment also resulted from this work. Fig. 4 represents the result from application of high-resolution wave number estimation techniques combined with optimally constrained linear inversion [5]. The figure indicates the seabed to be comprised of multiple layers over varying thickness with different sound speeds. Inversion based on wave number estimates requires acoustic pressure to measured as a function of range. In this work, this was accomplished by employing a synthetic aperture created by the relative motion between a fixed receiver and moving source. As indicated in Fig. 4, this approach provides fairly high spatial resolution. However, creating the synthetic aperture can be time consuming depending on the relative rate of motion. An alternative approach based on modal travel time estimates was developed as part of this work to provide spatial dependent seabed information. For a limited number of sources and receivers spread over an area this provided course resolution, however, data collection can be quite fast. Fig. 5 illustrates this approach applied to SW06 data with details provided in [6].

In FY11 and FY12, the work focused on application of approaches tested and developed during the previous years to systems comprised of operational assets, in particular GPS equipped AN/SSQ 53F sonobuoys. For this work, acoustic data were measured on both the MOMAX research buoys and operational sonobuoys at frequencies between 50 and 1000 Hz. The operational sonobuoys are designed to be air-deployed with data transmitted back to the aircraft over VHF. The VHF antenna on the buoy is located in a small float the surface of the ocean. For the experiment operated from the ship, the receiving antenna was much lower than it would be if located on an aircraft and thus the range to which data could be received from the buoy was limited. Nevertheless, at ranges less than 3 km, the data was of very high quality. At greater ranges, GPS data was unreliable and ranges had to be estimated.

The data observed on the two systems were analyzed for their wave number characteristics to be used in geoacoustic inversion. The resulting wave number spectra for four frequencies from the two systems are shown in Fig. 6. In general, the dominant wave numbers observed on both systems were nearly the same. Although the amplitudes for individual wave number peaks were not-equal, only wave numbers corresponding to locations of the peaks are used in the inversion, so there is little impact on the results. These data, expressed in terms of modal eigenvalues as determined by the peak locations were used in a linearized inversion scheme [2]. The resulting sound speed fields inferred from data collected on the two systems were remarkably consistent as indicated in Fig. 7. Although not discussed here, the two results are well within the expected error variance for the method. These results are promising for the development of an inversion application based on the use of operational sonobuoys during routine navy activities.

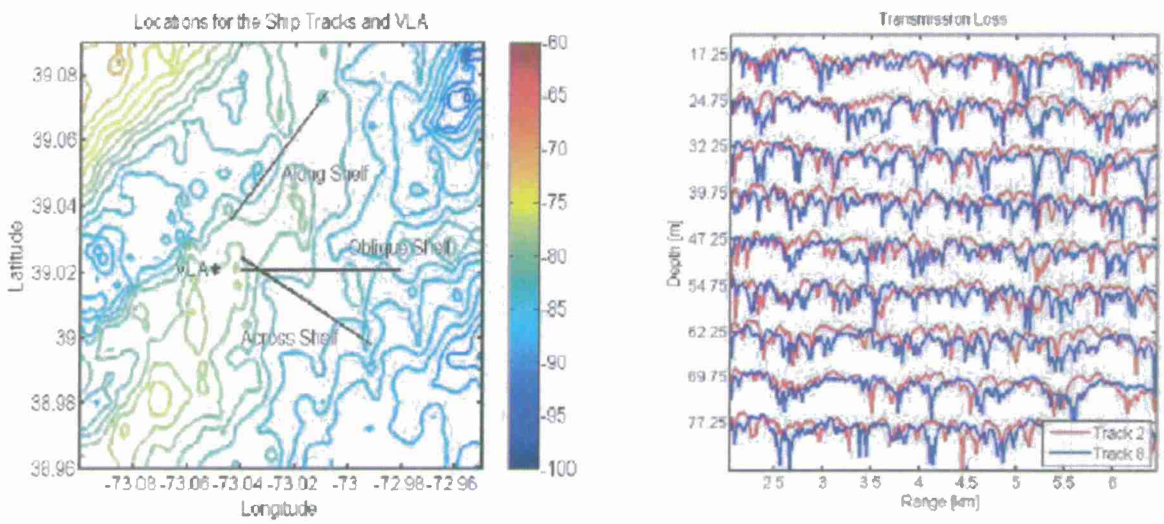
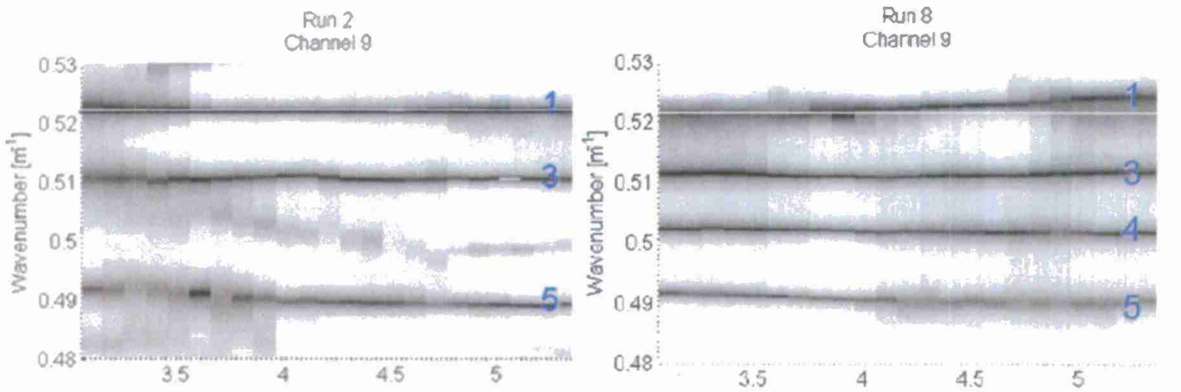


Fig. 1 (Left Panel) Radial tracks along which towed cw data were collected. (Right Panel) Magnitude of pressure fields (50 Hz) measured at all depths on the VLA for Track 2 and Track 8 oriental along the shelf. Track 2 and Track 8 data were collected 5 hours apart and have distinctly different modal interference patterns due to different oceanographic conditions.



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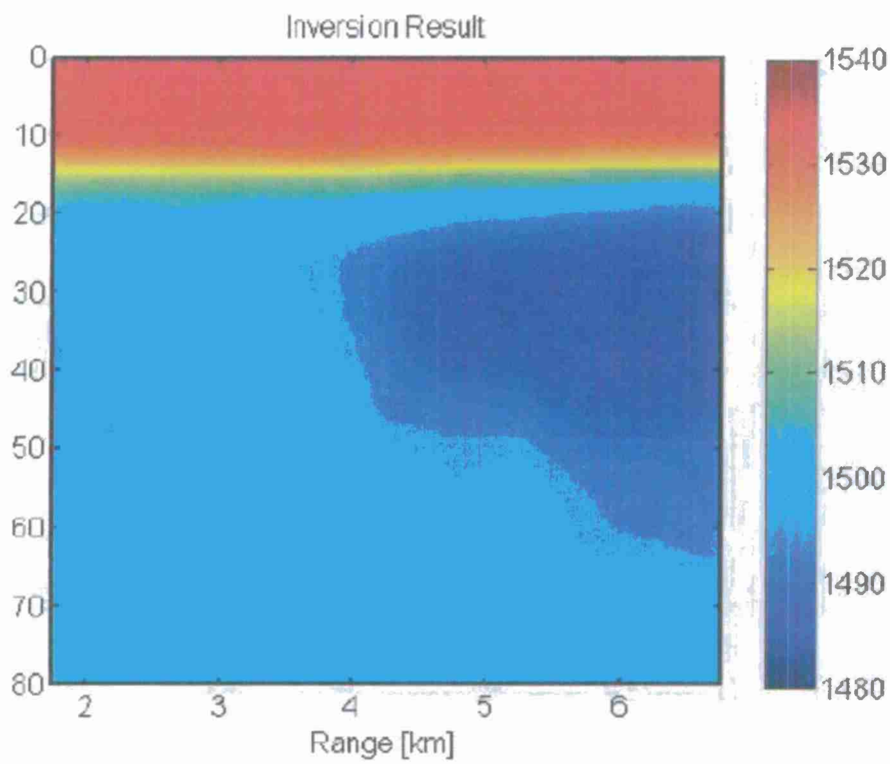

Fig.3 Inversion result for water column sound speed obtained from range-dependent wave number estimates of track 8 data. A general cooling of the water column at the far end of the track can be seen as indicated by the lower sound speed in that region.

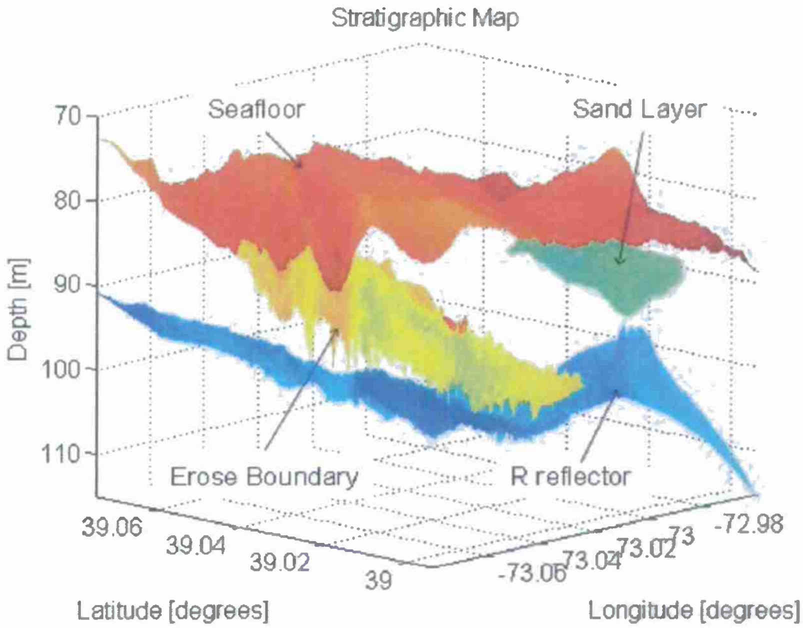

Fig.4 Geoacoustic inversion was applied to data collected along three source/receiver tracks oriented along, across, and oblique to the shelf bathymetry as indicated in Fig 1. Combining the inversion results with high-resolution CHIRP seismic reflection data range-dependent geoacoustic inversion results were extrapolated to cover the area between the tracks. Layer interfaces bounding regions with the same sound speed resulting from the inverion process are indicated in the right panel.

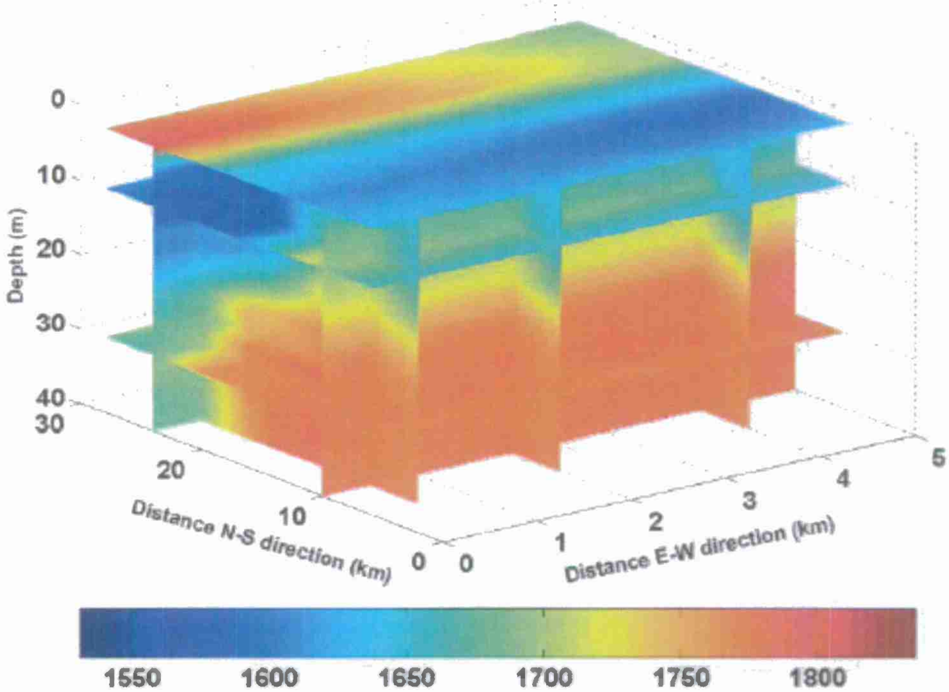

Fig. 5 Sediment sound speed inferred from modal travel time data for the source located 15 km from the array location shown in Fig. 1. The inversion results indicate the spatial variability of the sediment sound speed in the region.

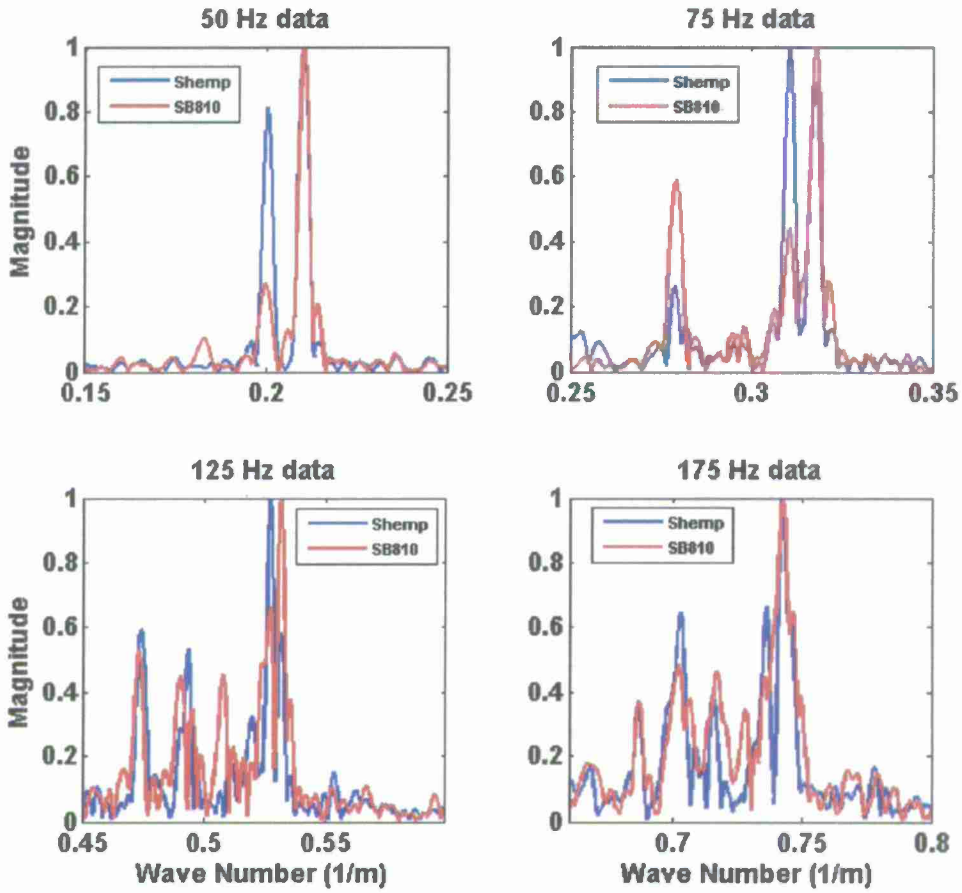

Fig. 6 Wave number spectra estimated at four different frequencies from data measured on the MOMAX buoys (blue) and the Operational Sonobuoy (red). Although the peak amplitudes are different, the peak locations are nearly the same between both systems. The peak locations indicate the modal eigenvalues which are used as the input data for inferring geoacoustic properties.

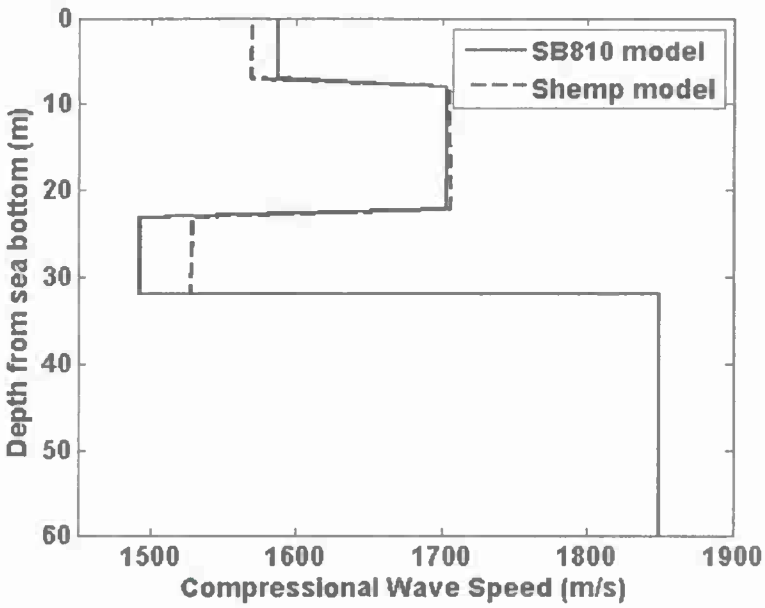

Fig. 7 Sound speed profile in the sediment inferred from modal eigenvalues estimated using MOMAX (dashed) and Operational (solid) sonobuoys.

IMPACT/APPLICATIONS

The application of these results is for geoacoustic inversion in range-dependent shallow water regions. The results are directed to suggest ways to account for and deal with the variability inherent in the watercolumn in shallow regions. In addition, the high-resolution methods reduce the apertures required to extract modal information resulting in more localized inversion results. The work is being adapted for use in operational systems and shows great promise.

RELATED PROJECTS

This work was a component of SW06. The approaches being developed recognize the complexities of shallow water waveguide environments and seek to account for them. The basic research elements of this program can lead to benefit programs aimed at exploiting operational assets for battlespace characterization. The applied part of this program was supported by the Oceanographer of the NAVY Rapid Transition Program (RTP) under grant N00014-09-1-0505.

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HONORS/AWARDS/PRIZES

Kyle M Becker was awarded the 2011 A.B. Wood Medal presented by the Institute of Acoustics, U.K. He was presented with the award at the 2012 European Conference on Underwater Acoustics in Edinburgh, Scotland, U.K 6 July 2012.

In December, 2009 Megan S. Ballard was awarded the Ph.D. Acoustics by the Pennsylvania State University. Her thesis was based on this research and is titled: "Optimized Contraints for the Linearized Geoacoustic Inverse Problem"